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REVIEW OF METEOROID ENVIRONMENT

BASED ON RESULTS FROM

EXPLORER XIII AND EXPLORER XVI SATELLITES

By

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REVIEW OF METEOROID ENVIRONMENT
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NASA Headquarters

## ABSTRACT

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The EXPLORER XIII (1961 CHI) and EXPLORER XVI (1962 BETA CHI I) Satellites are briefly described and detailed information on the meteoroid detector experiments incorporated is presented.

Data from the experiments are analysed and compared with currently used theories, observations, and laboratory impact studies.

Time histories of the penetrations encountered during the first four months of the EXPLORER XVI satellite's lifetime are given and penetration rates based on the effective time-area exposure to meteoroid influx are derived. These penetrations in the detector materials are compared with predicted estimates of other investigations and theories.

The correlation between the meteoritic encounter frequency and the number of penetrations obtained is given and this correlation is discussed in terms of extending the knowledge of meteoroid hazard to spacecraft in the near-earth environment.

## INTRODUCTION

One of the hazards in the space environment is the possible encounter with extraterrestrial debris known generally as "meteoroids." It is clear that a meteoroid impact with a space vehicle could be a catastrophic event. Consequently, the effects of these meteoritic encounters on space vehicles are a matter of concern in the design of spacecraft for various space missions.

To properly evaluate the hazard from meteoroid impacts the distribution of interplanetary matter in the solar system and the characteristics of crater formation in and penetration of spacecraft structures by such impacts must be determined.

A great number of papers have been written on the subject of penetration of spacecraft by meteoroids. Some of these papers are listed in references 1 thru 5. In all of these papers knowledge of the distribution of interplanetary matter in the solar system has been obtained from visual, optical, and radio-measurements of meteors, from accretion measurements in the earth's atmosphere and on the earth's surface, and from direct measurements using rocket probes and satellites, while information concerning the characteristics of impact cratering and penetration from meteoroid impacts have been obtained from laboratory hypervelocity impact studies. Due to the indirect nature of such assessments these papers give only an estimate of the hazard. Therefore a more accurate appraisal of the meteoroid hazard is required. Undoubtedly the best way to accurately determine the hazard is to expose structural skin specimens to the meteoritic environment and make direct measurements of penetration rates. This basically was the objective of the Explorer XIII and Explorer XVI satellites.

It is the purpose of this paper to present the results obtained from the Explorer XIII (1961 CHI) and Explorer XVI (1962 BETA CHI I) satellites and from a comparison of these penetration rates with predicted estimates and meteoritic encounter frequency to reappraise the meteoroid hazard to spacecraft.

Further a more accurate distribution of interplanetary matter in the solar system will be determined from a correlation of the penetration flux as obtained from the measured penetration rates with ground observations of meteors and an interpretation of the dust content in the Zodiacal cloud.

## DESCRIPTION OF SPACECRAFT AND EXPERIMENTS

### Spacecraft

Figure 1 is a photograph of the Explorer XIII and Explorer XVI satellites. These spacecraft were identical except for material thickness distribution. The satellites were cylindrical in shape, approximately

186 cm long and 56cm in diameter. They were built around the last-stage rocket motor of the launch vehicle the spent case of which remained as part of the orbiting spacecraft. The weight of the Explorer XIII including burned-out rocket motor was about 86 kilograms, while the corresponding weight of the Explorer XVI is about 106 kilograms.

Each of these spacecraft incorporates five different experiments to obtain information on meteoroids. Figure 2 is a schematic of the Explorer XIII and Explorer XVI satellites showing the location of the experiments. These experiments include impact detectors (piezoelectric transducers) and cadmium sulfide cells mounted on the forward part of the spacecraft; pressurized cells and additional impact detectors located on the base plate of some of the pressurized cells which are mounted on the center section of the spacecraft; and stainless steel covered-grid detectors and copper-wire detectors mounted on the aft part of the spacecraft. These experiments are described in more detail below.

## Experiments

The pressurized cell experiment, developed at the NASA Langley Research Center, is the primary experiment on the spacecraft. The author and Charles A. Gurtler of Langley are the experimenters.

Figure 3 is a drawing of the pressurized-cell detector. A total of 160 of the annealed beryllium-copper cells are mounted around the periphery of the rocket motor case in 5 rows of 32 cells each. Each cell was filled with helium. When the cell is punctured, the gas leaks out and the pressure loss actuates a switch that signals the telemeter of the puncture. Thus, after one puncture, the cell cannot indicate additional punctures.

A second experiment is the stainless steel covered grid detector developed by the NASA Lewis Research Center. Elmer H. Davison of Lewis is the experimenter. Figure 4 is a sketch of this detector. The detectors, made from type 304 stainless steel segments, were mounted around the base of the fourth-stage motor and bonded to the outside of a thin continuous grid circuit. A puncture of the stainless-steel cover will break the circuit beneath it, producing a change in electrical resistance.

A third experiment was developed by the NASA Goddard Space Flight Center by Luc Secretan. A sketch of this experiment is shown in figure 5. Forty-six of these copper-wire cards are mounted on a cylindrical structure aft of the steel-covered grids. Each card consists of a continuous winding of 0.0051 - or .0076-cm copper-wire closely wound on a melamine card. Each 0.0051-cm card forms a separate detector, but the 0.0076-cm detectors are formed from two cards in series. Detector operation is similar to that of the steel-covered grids in that a puncture, or break, of the wire causes a change in circuit resistance. These detectors, as well as the two types of puncture detectors previously described, cannot provide additional data once a puncture has occurred. The physical characteristics of these experiments are shown in Table I.

Piezoelectric crystal transducers for detection of impacts and having three levels of momentum sensitivity were developed by the NASA Langley Research Center. Alfred G. Beswich is the experimenter. Twenty of the 0.0127-cm thick pressurized cells were instrumented with transducers having the intermediate sensitivity level. A sketch of the transducer located beneath the base plate of the cell is shown in figure 6. Two acoustically isolated "sounding boards" on the forward section of the spacecraft, as shown in figure 7, were used for the remaining two levels of sensitivity.

Each of the two sounding boards was sensitized to impact by a pair of piezoelectric crystals, mounted on its underside and electrically paralleled. The impact event signals from both sounding boards are sent to an amplifier, which equalizes the effective sensitivity of the two sounding boards which in effect thus function as one transducer, with the high-and low-sensitivity threshold levels are selected electronically.

The characteristics of the impacting detecting systems are shown in Table II.

The fifth experiment used on these satellites is illustrated in figure 8. This is the cadmium sulfide cell developed by the NASA Goddard Space Flight Center. Luc Secretan is again the experimenter.

The experiment consists of a light-sensitive cadmium sulfide element mounted beneath a sheet of 0.00056-cm plastic film (Mylar) with vapor-deposited aluminum on both sides. The purpose of the experiment is to determine the size of the hole left in the plastic (Mylar) by the penetrating particle, by measuring the change in electrical resistance caused by the sunlight admitted through the hole. Two of these cells, with a total exposed area of 48-square centimeters, were mounted on the nose section of the satellites.

## ORBITAL PARAMETERS

The Explorer XIII satellite was launched due east from the NASA Wallops Station by means of a Scout launch vehicle on August 25, 1961 and injected into a near-earth orbit. Due to a large injection angle and resulting low perigee the achieved orbit had a lifetime of only 2 1/2 days and the Explorer entered the earth's atmosphere on August 27, 1961.

The Explorer XVI, was launched, at a heading of 130° (from north), from the NASA Wallops Station by means of a Scout launch vehicle on December 16, 1962 and injected into the desired near-earth orbit. Table III shows a comparison of the predicted orbital elements of the Explorer XVI with the actual measured elements as determined by the NASA Goddard Space Flight Center on May 1, 1963.

## RATE OF METEOROID PENETRATIONS

### Accumulative Penetrations

Explorer XIII - Although the Explorer XIII had a very short life, several successful interrogations of the telemeters were made and significant data were obtained on the meteoroid environment. During the 2 1/2 days life, no penetrations were recorded in any of the experiments. This result will be discussed in respect to the Explorer XVI results presented below.

The counting rates obtained from the impacting detector experiment on the Explorer XIII indicated impacts considerably higher than were anticipated. These high counting rates have been observed by other experimenters during the first few days in orbit. The explanation is thought to lie in mechanical and thermal stabilizing processes, debris in the vicinity of the satellite resulting from ascent events, outgassing, and possibly other factors. Since it was not possible to isolate these effects from actual meteoritic encounters, accurate impact rates could not be determined during the short life of this satellite.

Explorer XVI - Explorer XVI is performing as designed and is providing significant data on the penetrating capability of meteoroids in thin structural materials. In addition data are being obtained on the frequency of impact by meteoritic particles.

Figure 9 shows the accumulated punctures as a function of time for the 0.0025-cm and 0.0051-cm beryllium-copper pressurized cells as well as the 0.0025-cm stainless steel-covered grid detectors. The data presented extend over the time period from December 16, 1962 (launch) thru April 18, 1963. During the four months in orbit, thirty-three-0.0025-cm beryllium-copper and nine-0.0051-cm beryllium-copper penetrations have been recorded. There have also been three-0.0025-cm stainless steel penetrations recorded in this time period as well as several penetrations of the vapor deposited 0.00056-cm Mylar film of the cadmium-sulfide experiment. As of April 18, 1963, one cadmium-sulfide cell is now completely saturated with sunlight and is no longer useful as a meteoroid detector. These results will be reported elsewhere at a later date. No penetrations had been received thru April 18, 1963 in the 0.0076-cm and the 0.0152-cm stainless steel-covered grid experiment nor in the 0.0051-cm and 0.0076-cm copper wire card experiment. Several hundred impacts have been received by the impact experiment, but as yet these data are not completely analyzed.

From figure 9 the randomness of the penetrations is apparent.

## Penetration Rates

The penetration rates were computed using the information shown in Table I and the data presented in figure 9. That is, the rates were computed for the total number of penetrations received thru April 18, 1963 taking into account the decrease in exposed area following each penetration. As pointed out previously, once a segment of an experiment receives a penetration it no longer can record any further penetrations. The penetration rates in the corresponding material thickness are shown in Table IV.

Tests have been conducted at the NASA Langley Research Center to ascertain a correlation of penetration depth in beryllium-copper with that in one of the more common structural materials such as aluminum. The results of these tests are shown in Figure 10. Aluminum projectiles 0.158-cm in diameter were fired into quasi-infinite thick aluminum and beryllium-copper targets at velocities up to about 5.2 km/sec and respective depths of penetration determined. From these data it appears that the penetration depth in aluminum is about twice the depth in beryllium-copper for the same particles and velocities. Calculations were performed to correlate the penetration depth in beryllium-copper with that in stainless steel. Results of these calculations indicated that the penetration depth in both materials is approximately the same.

Using these results and correcting for the shielding effect of the earth, the penetration rates are plotted at the corresponding thickness of aluminum and compared with two estimates of the penetration hazard in Figure 11. The error bars on the points are the 95% confidence limits. No confidence limits are placed around the 0.0025-cm stainless steel data point since no statistical significance can be given to results derived from so few events.

The upper curve of predicted penetrations has been determined from the estimate of the distribution of interplanetary matter by Whipple (1957), reference 3, and the experimental penetration criteria of Charters' and Summers' (1958), reference 6. The lower curve has been determined from the estimate of the distribution of interplanetary matter by Watson (1941), reference 7, and the theoretical penetration of Bjork (1961), reference 4. These two estimates were chosen since they represent what have been believed to be reasonable limits on the expected penetration rates. It is seen that there is a difference of over three orders of magnitude between the curves. These differences are explained elsewhere, (reference 8), and will not be discussed here.

It is clear from the penetration rates established by the Explorer XVI data in the region where these data are statistically significant, that the Whipple (1957) distribution combined with the Charters' and Summers' (1958) penetration criteria greatly over-estimates the meteoroid hazard, while the Watson (1941) - Bjork (1961) estimate falls slightly below the actual measured data.

On the basis of these data it appears that the Whipple-Charters' and Summers' estimate if used would result in structural weights for protection from meteoroids that would be excessive.

The Explorer XVI data do not in themselves clearly define the expected penetration rates over a wide range of material thicknesses; however, the use of these data together with ground observation of meteors will allow a more realistic estimate of the expected hazard.

## Correlation Between Meteoritic Encounter Frequency and Number of Penetrations

Presented in figure 12 are cumulative meteoroid impact rates as a function of mass as determined from several ground observations as well as direct measurements by probes and satellites. Shown are the Whipple (1957), Watson (1941), as well as the Whipple (1963) (reference 9) estimate based on optical measurements of meteors. Also shown is the Watson (1941) estimate revised by Whipple in 1963 (reference 9). The curves labeled v. d. Hulst (1947) (reference 10) and Ingham (1961) (reference 11) are based on Zodiacal light measurements. Direct measurements are shown by the curves labeled Alexander (et al, reference 12) and Soberman and Heminway (reference 13) as well as the data points labeled Pioneer I (reference 14) and Mariner II (reference 15). The Explorer XVI data points were determined from the previously presented data thru the use of the Bjork penetration criteria. All data presented in this figure assume a mean meteoroid density of 0.44 $gms/cm^3$ and a mean velocity of 30 km/sec. which is consistent with the analysis by Whipple (1963) based on optical meteor observations.

The measurements by Alexander, et al were made near-earth, while the Pioneer I data were obtained to distances of several earth radii. The Mariner II data were obtained over distances from the earth to the vicinity of Venus. From these data it is immediately apparent that the impact rates based on direct measurements decrease as the distance from the earth increases. This result has also been discussed by other experimenters, (see references 16, 17, and 18.) Also there is good agreement between the revised Watson curve and an interpretation of the dust content in the Zodiacal cloud. A most interesting result is shown in the agreement in the flux of particles capable of penetrating thin metallic skins (Explorer XVI data) and the Zodiacal light curve (Ingham 1961) The Whipple 1963 curve is based on the Hawkins-Upton influx rate (reference 19) and extrapolates these data to smaller meteoritic masses ($m < 10^{-3}$ gms). There is no evidence to indicate that influx of small meteoroids will follow the same distribution as the mass of larger ones.

Therefore based on the data presented there is no real discrepancy between the ground observations, and we may expect that the true distribution of interplanetary matter at one astronomical unit to be represented by the Ingham (1961) data and the revised Watson estimate. This result has also been discussed by Kaiser (1963), reference 20. However, near the earth the distribution of meteoroids may be 3-6 orders of magnitude greater than the interplanetary distribution as indicated by the direct measurements of Alexander et al and Soberman and Heminway for masses less than about $10^{-6}$ gms.

There is a great discrepancy (over 4 orders of magnitude) between the Explorer XVI data and the data of Alexander et al. These direct measurements were made near the earth and their comparison with the other data indicate that although the earth is encompassed by a dust belt of relatively high spacial density as compared to interplanetary space only a small percentage of these meteoritic particles are able to penetrate thin metallic surfaces.

If this is the case it may only be necessary to design spacecraft for protection against penetrations from a very small fraction of the meteoritic matter in the dust cloud about the earth. On this basis, the weight of material required for protection is considerably smaller than that required based on previous estimates of the penetrating capabilities of meteoroids in the neighborhood of the earth. On the other hand it would be necessary to consider the complete content of meteoritic material in the design of optical surfaces and thermal coatings.

Such considerations lead to a variation of the average number of meteoritic impacts with meteoritic mass as shown in figure 13.

For missions at one astronomical unit the lower curve is an estimate of the average number of meteoritic encounters of a given mass or larger. For missions near the earth the upper curve should be considered in the design of optical surfaces and thermal coatings. The number of encounters may increase by a factor of 5 to 10 during periods of recognizable sporadic showers and several of the periodic meteor showers. For short exposure times to the space environment, adverse effects may be present during these known or sporadic meteor showers. However, for long exposure times the distribution curves shown in figure 13 should be an effective expectation of the impact frequency. At radial distances from the sun between 1.5 and 5 astronomical units the collision hazard from asteroidal debris may be greater than at one astronomical unit. Preliminary results from the Mariner II space probe (reference 15) indicate that the spacial density at radial distances less than one astronomical unit is about $10^4$ times less than that in the neighborhood of the earth and is in agreement with some interpretation of the dust content in the Zodiacal cloud.

## CONCLUDING REMARKS

The results obtained from the Explorer XVI (1962 BETA CHI I) satellite have provided the first known penetrations by meteoroids in thin metal sheets and these results have been used to determine the accuracy of two estimates of the meteoroid hazard to spacecraft.

It has been shown that the probability of damage in metal sheets having thicknesses of about 0.0025-cm is considerably less than the Whipple-Charters' and Summers' estimate and slightly greater than the Watson-Bjork estimate.

A comparison of meteoritic encounter frequency and the number of penetrations obtained by the Explorer XVI has shown that although the earth is encompassed by meteoritic material of relatively high spacial density as compared to interplanetary space only a small percentage of these meteoritic particles are able to penetrate thin metallic surfaces. If this is the case the weight of material required for protection against penetration is considerably smaller than that required based on previous estimates of the penetrating capabilities of meteoroids in the neighborhood of the earth.

Based on available knowledge and data it has been determined that there is no longer any serious discrepancy between the meteor data extrapolated to smaller masses and those obtained from measurements of the dust content in the Zodiacal cloud. A spacial distribution has been derived extending from meteors producing fireballs to meteoritic particles that are small enough to remain in the solar system.

This distribution of interplanetary matter combined with accurate cratering and penetration criteria will in time define the meteoroid hazard.

## ACKNOWLEDGEMENTS

The author wishes to thank all experimenters who contributed freely of their data prior to formal publication as well as all others connected with the Explorer XVI Meteoroid Satellite Project. In particular the author expresses his appreciation to J. Warren Keller for the many helpful discussions during the preparation of this paper.

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## FIGURE CAPTIONS

TABLE I

PHYSICAL CHARACTERISTICS OF EXPERIMENTS

EXPLORER XIII

| Experiment | Material | Thickness, cm | Number of Segments | Area Sq. Meters |
|---|---|---|---|---|
| Pressurized Cells | Beryllium-Copper | 0.0025 | 60 | 0.845 |
| | Beryllium-Copper | .0038 | 40 | .562 |
| | Beryllium-Copper | .0051 | 20 | .281 |
| | Beryllium-Copper | .0064 | 20 | .281 |
| | Beryllium-Copper | .0127 | 20 | .281 |
| Grid | Stainless Steel | .0076 | 50 | .279 |
| | Stainless Steel | .0152 | 10 | .070 |
| Wire Card | Copper | .0051 | 14 | 0.064 |
| | Copper | .0076 | 32 | 0.146 |

EXPLORER XVI

| Experiment | Material | Thickness, cm | Number of Segments | Area Sq. Meters |
|---|---|---|---|---|
| Pressurized Cells | Beryllium-Copper | 0.0025 | 100 | 1.020 |
| | Beryllium-Copper | .0051 | 40 | .408 |
| | Beryllium-Copper | .0127 | 20 | .204 |
| Grid | Stainless Steel | .0025 | 32 | 0.145 |
| | Stainless Steel | .0076 | 24 | 0.192 |
| | Stainless Steel | .0152 | 4 | 0.024 |
| Wire Card | Copper | .0051 | 14 | 0.064 |
| | Copper | .0076 | 32 | 0.146 |

TABLE II

CHARACTERISTICS OF THE

METEOROID IMPACTING EXPERIMENTS

EXPLORER XIII AND EXPLORER XVI

Sounding Boards, (2), Type 410 Stainless Steel

| Size and Shape | Area, $cm^2$ | Sensitivity, dyne-sec |
|---|---|---|
| Conical Section<br>12.5 cm wide<br>0.079 cm thick<br>59.2 cm outside diameter<br>32.8 cm Internal diameter | 709 each<br>(1418 total) | 1.0 and 0.1 |

Pressurized Cell (20), Beryllium Copper

| Size and Shape | Area, $cm^2$ | Sensitivity, dyne-sec |
|---|---|---|
| Semi-cylindrical<br>18.8 cm long<br>4.93 cm diameter<br>0.0125 cm thick | 92.8 $cm^2$ each<br>(projected)<br>(1856 $cm^2$ total) | 0.4 |

TABLE III

ORBITAL ELEMENTS OF EXPLORER XVI

| | Predicted | Measured as of May 1, 1963 |
|---|---|---|
| Perigee altitude, km | 731.86 | 750.28 |
| Apogee altitude, km | 1,099.07 | 1180.23 |
| Inclination, deg | 51.43 | 52.004 |
| Period, Min | 103.20 | 104.378 |
| Eccentricity | .02519 | .02927 |
| Semimajor axis, earth radii | 1.15133 | 1.15133 |
| Mean anomaly, deg | 349.618 | 157.820 |
| Right ascension of ascending node, deg | 10.779 | 314.259 |
| Velocity at perigee, km/hr | 27,312 | 27,312 |
| Velocity at apogee, km/hr | 25,758 | 25,758 |
| Geocentric latitude of perigee, deg | -13.116 | 30.917 |

TABLE IV

EXPLORER XVI PENETRATION RATES

| Material | Thickness cm | Penetration Rate Number/$M^2$/sec |
|---|---|---|
| Beryllium-Copper | 0.0025 | $4.36X10^{-6}$ |
| Beryllium-Copper | .0051 | $2.62X10^{-6}$ |
| Stainless Steel | .0025 | $2.23X10^{-6}$ |

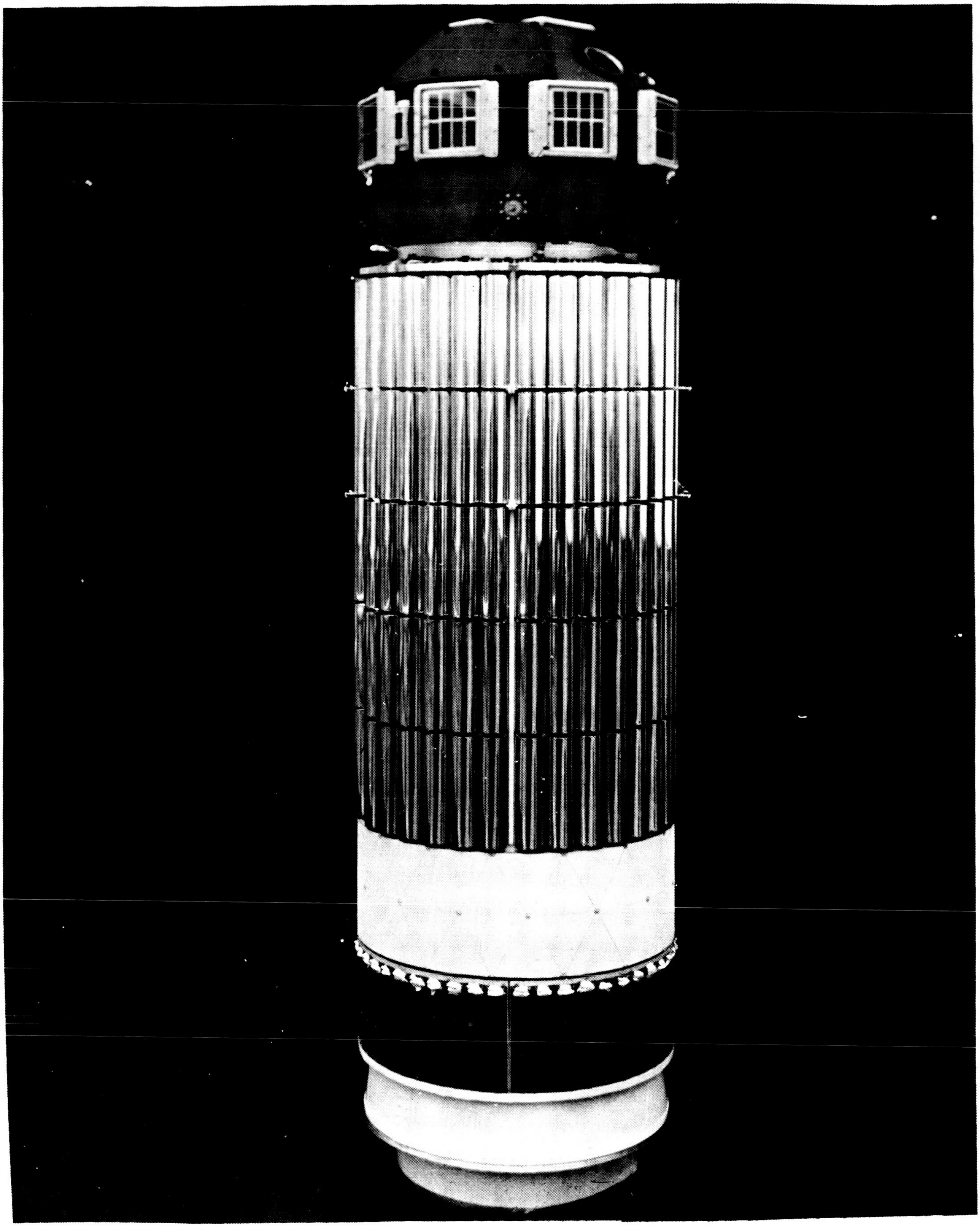


Figure 1.- Explorer XIII and Explorer XVI satellites.

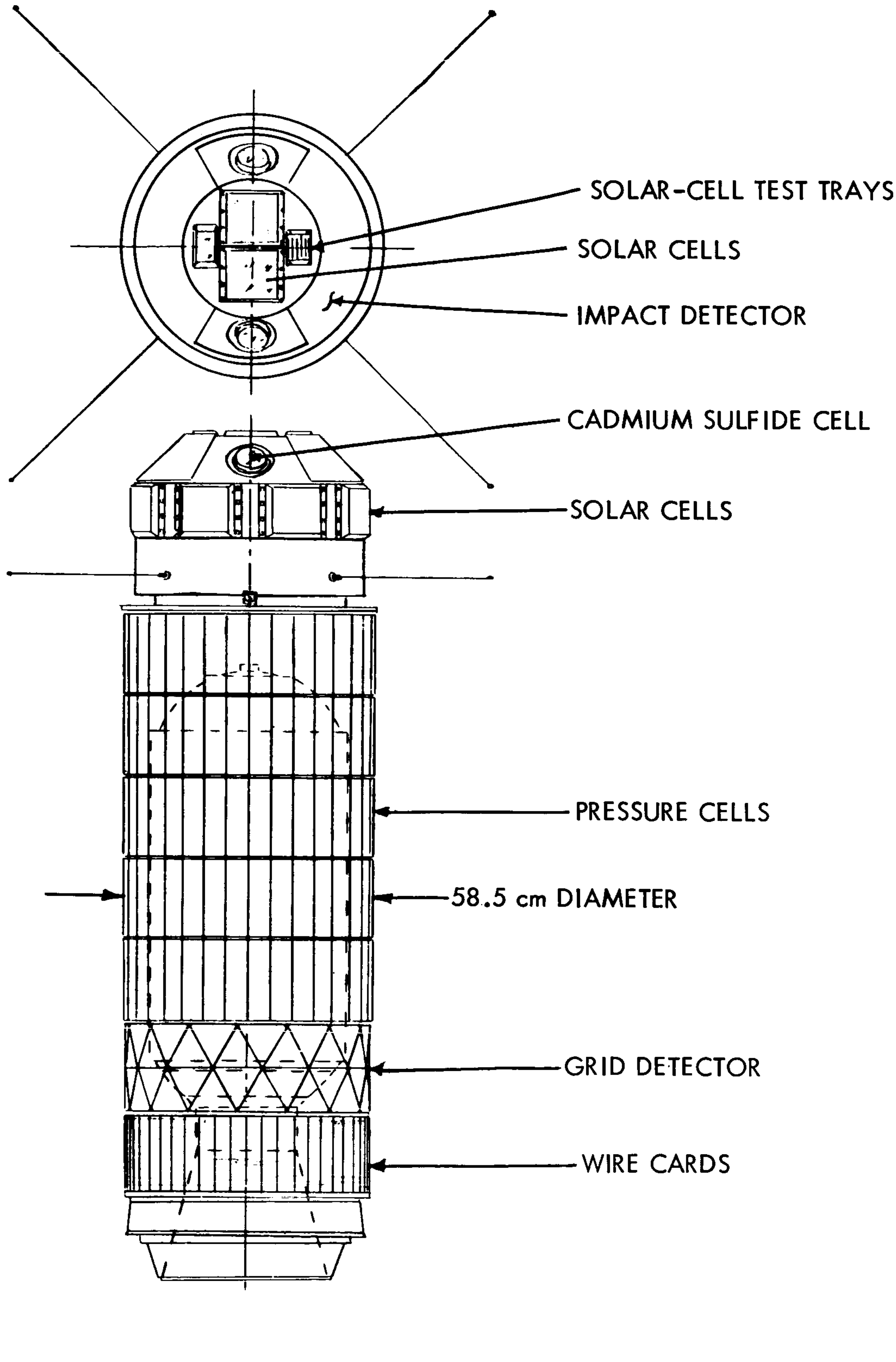



FIG. 2 - SCHEMATIC DRAWING OF EXPLORER XIII AND EXPLORER XVI.

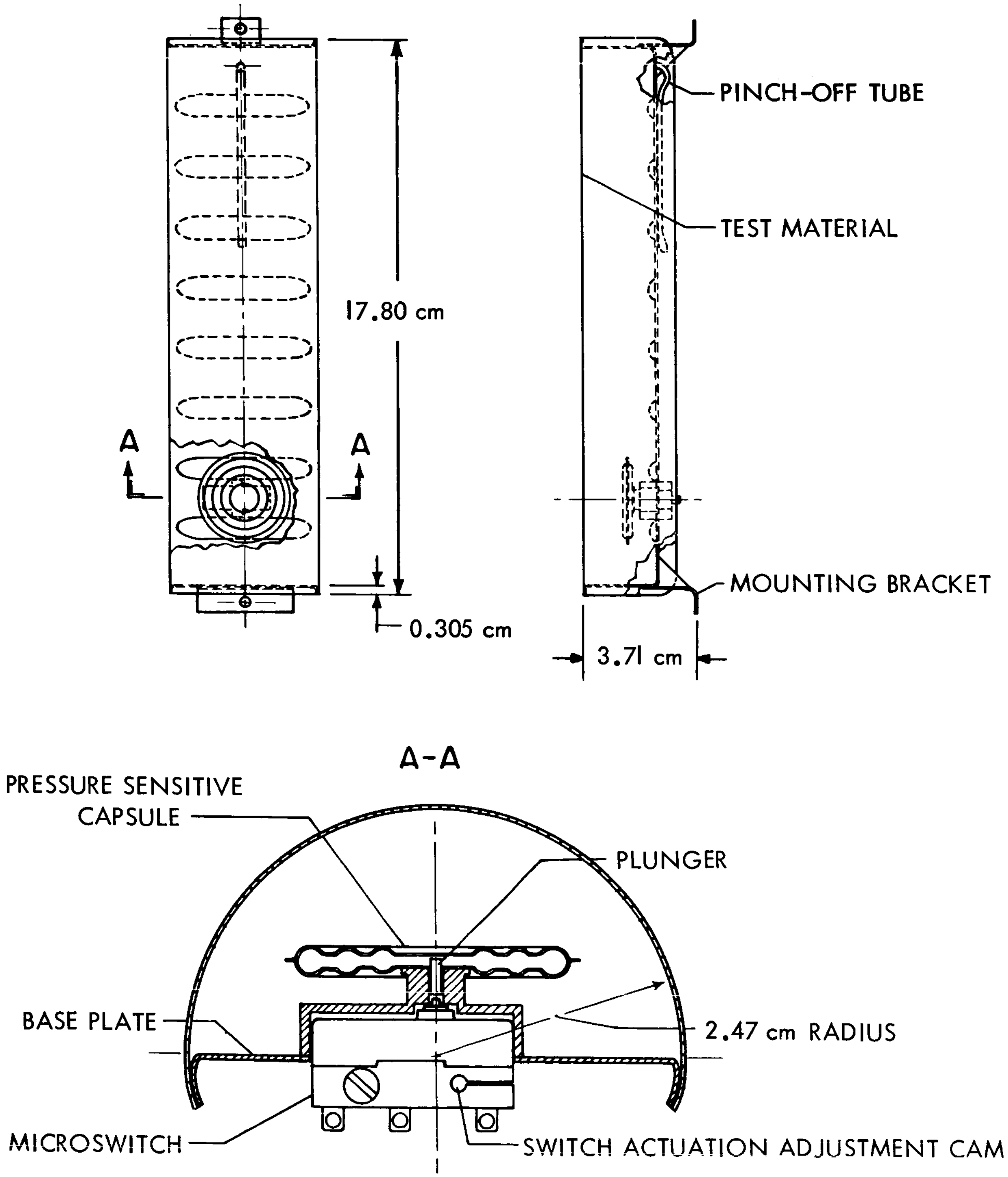



FIGURE 3 - SKETCH OF PRESSURIZED CELL EXPERIMENT

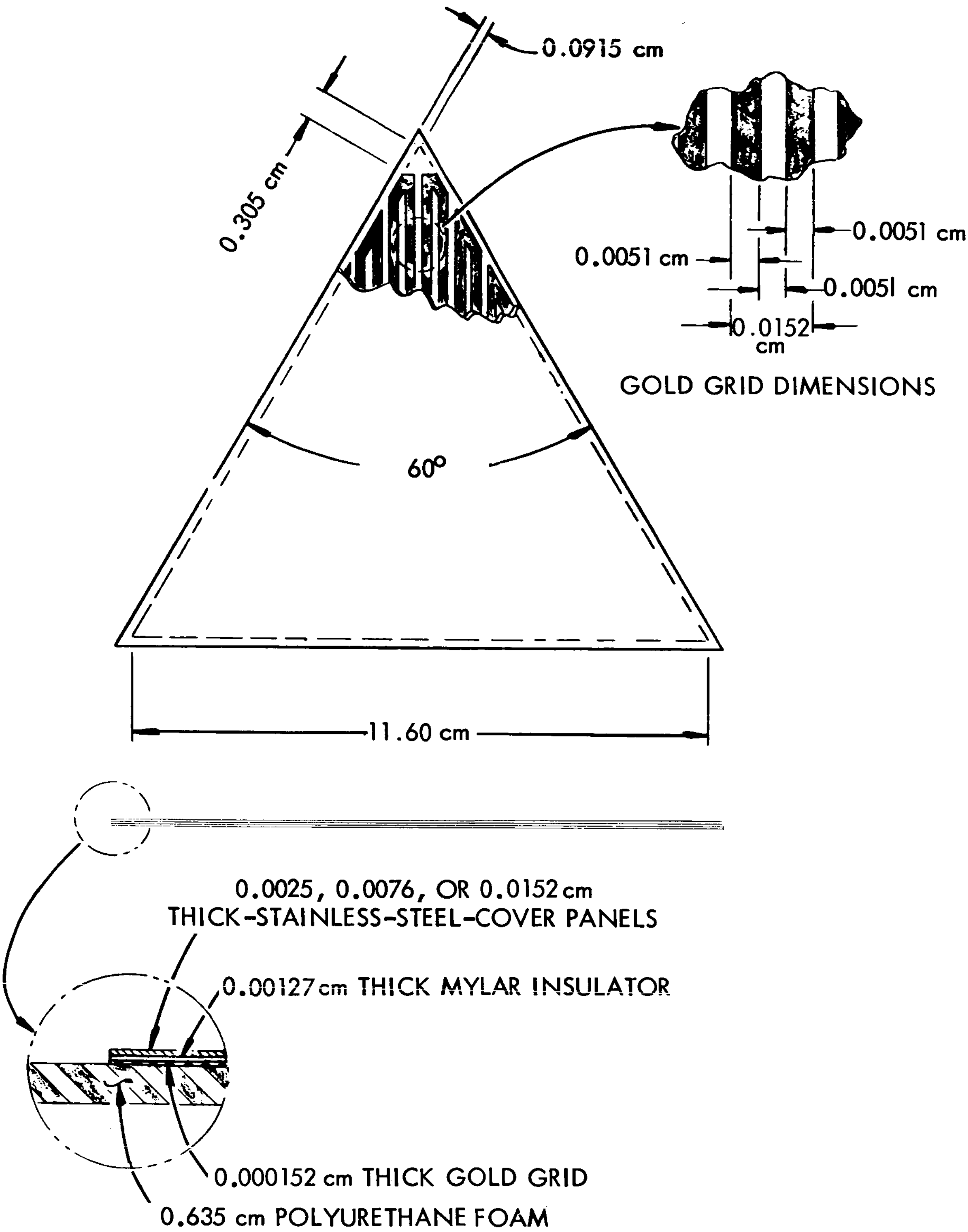



FIGURE 4. - SKETCH OF STAINLESS STEEL COVERED-GRID EXPERIMENT.

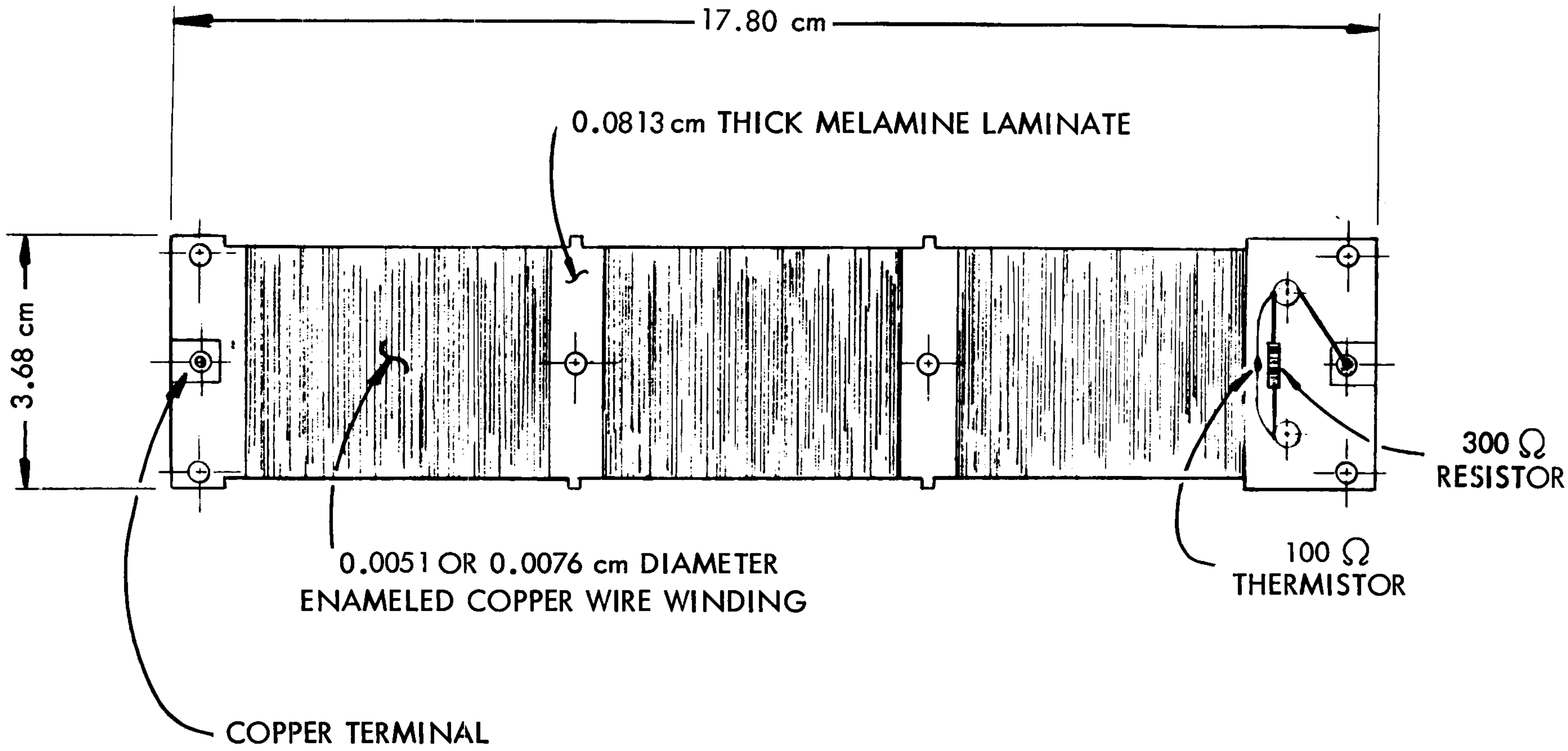



FIGURE 5. - SKETCH OF COPPER-WIRE CARD EXPERIMENT.

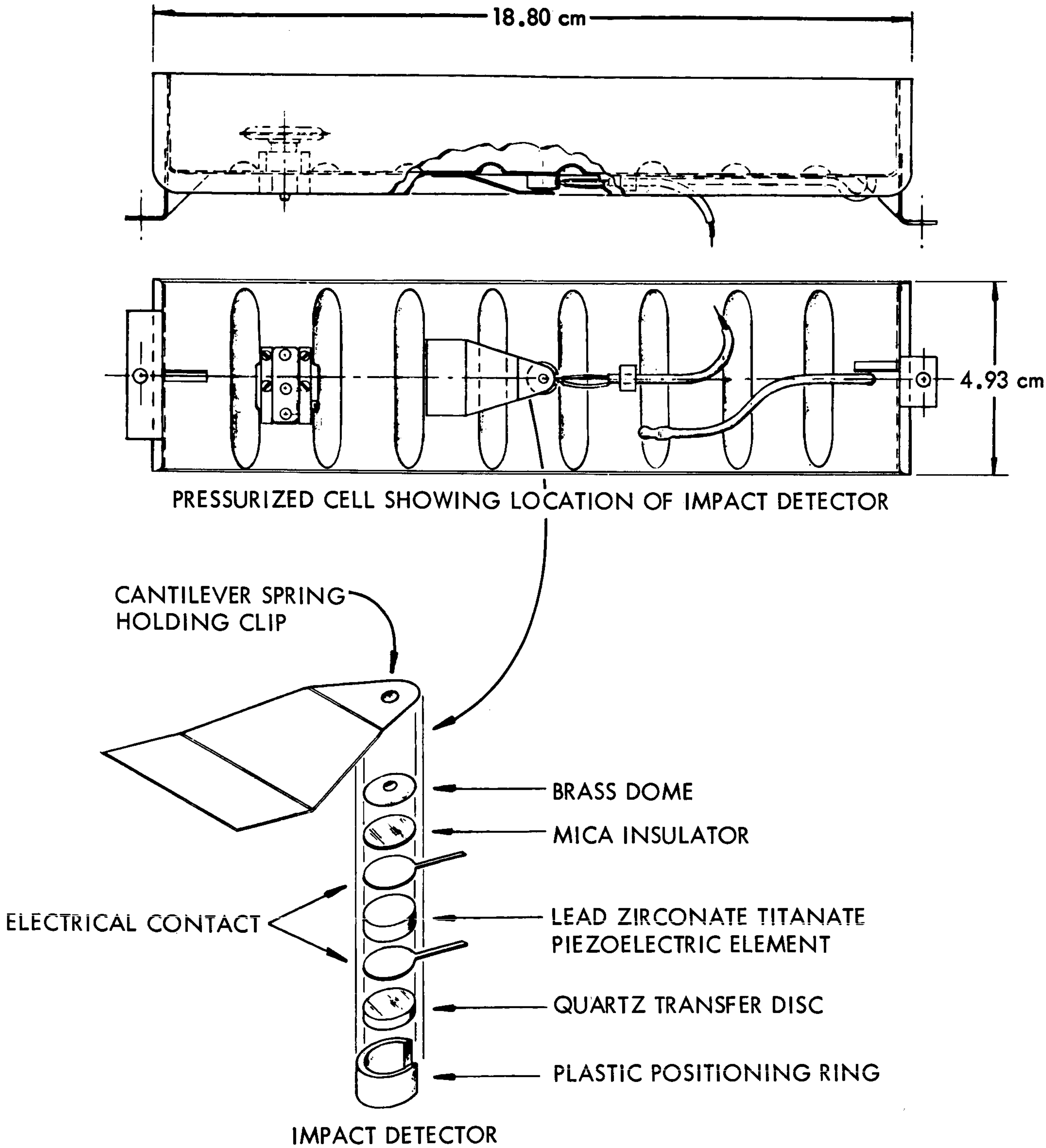



FIGURE 6 - SKETCH OF IMPACTING DETECTOR EXPERIMENT MOUNTED ON BASE OF PRESSURIZED CELL

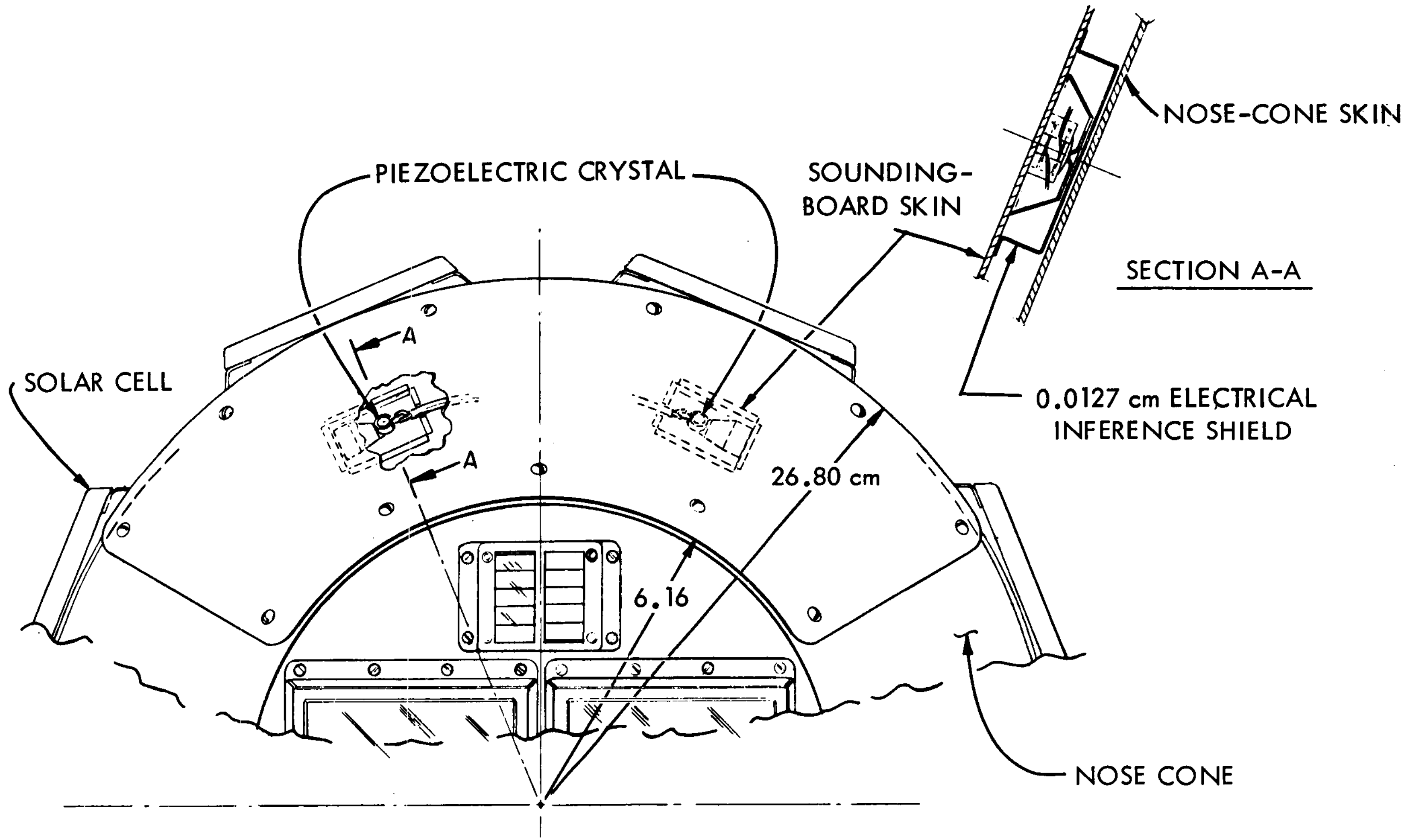
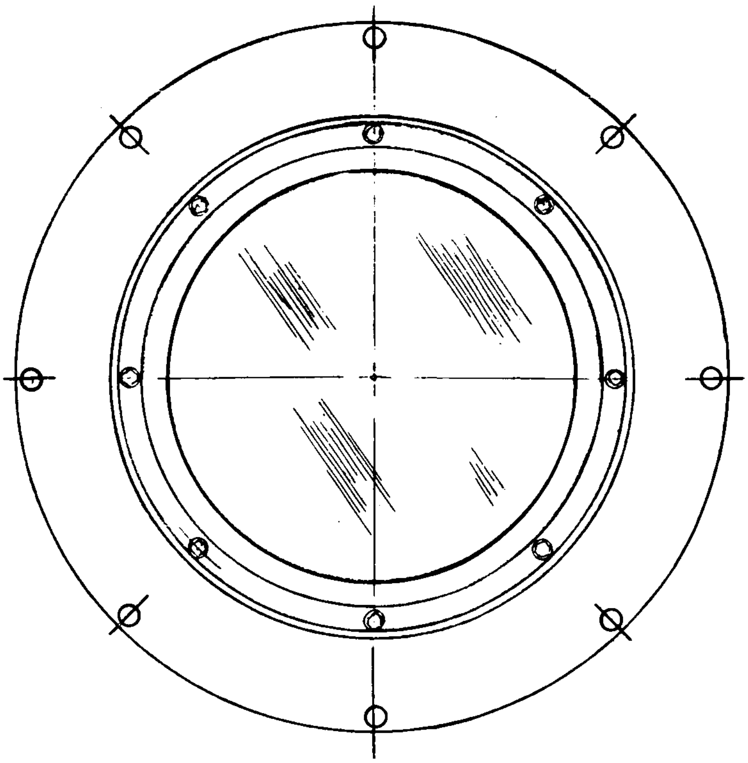



FIG. 7 - SKETCH OF IMPACTING DETECTOR EXPERIMENT MOUNTED UNDER "SOUNDING BOARDS".



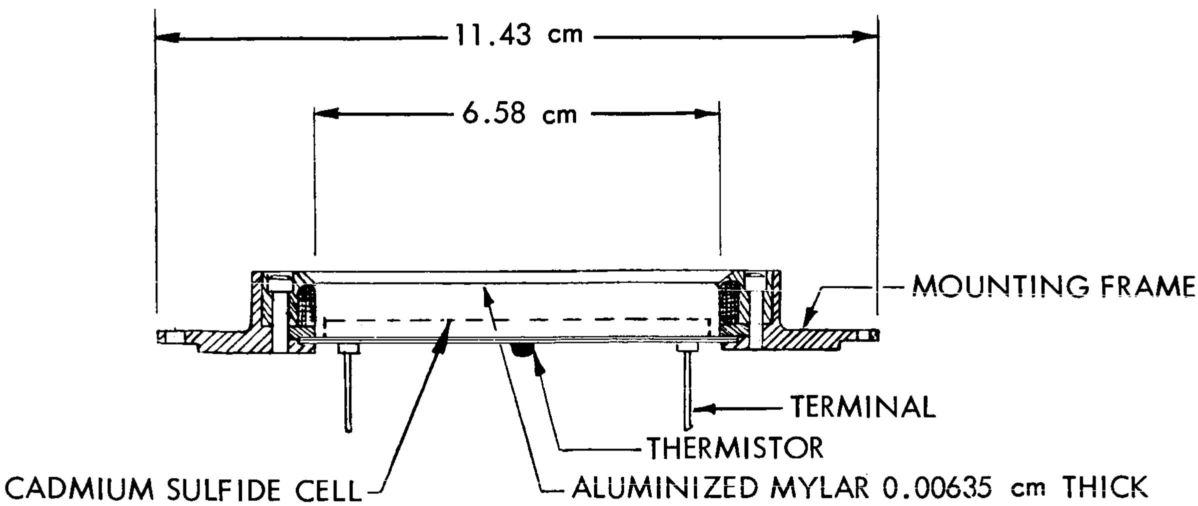



FIGURE 8 - SKETCH OF CADMIUM SULFIDE CELL EXPERIMENT

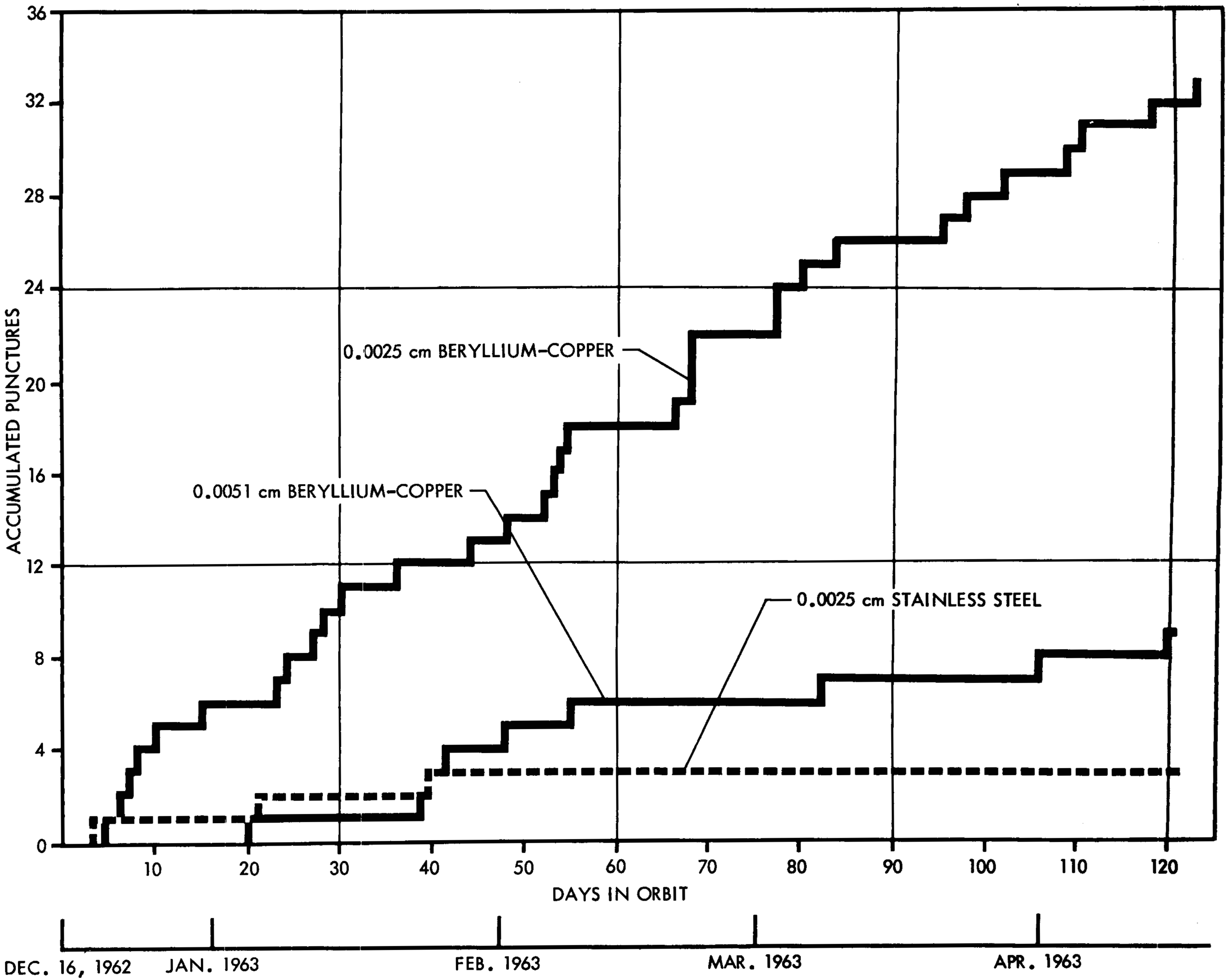



FIGURE 9 - ACCUMULATED PENETRATIONS RECEIVED BY THE EXPLORER XVI SATELLITE

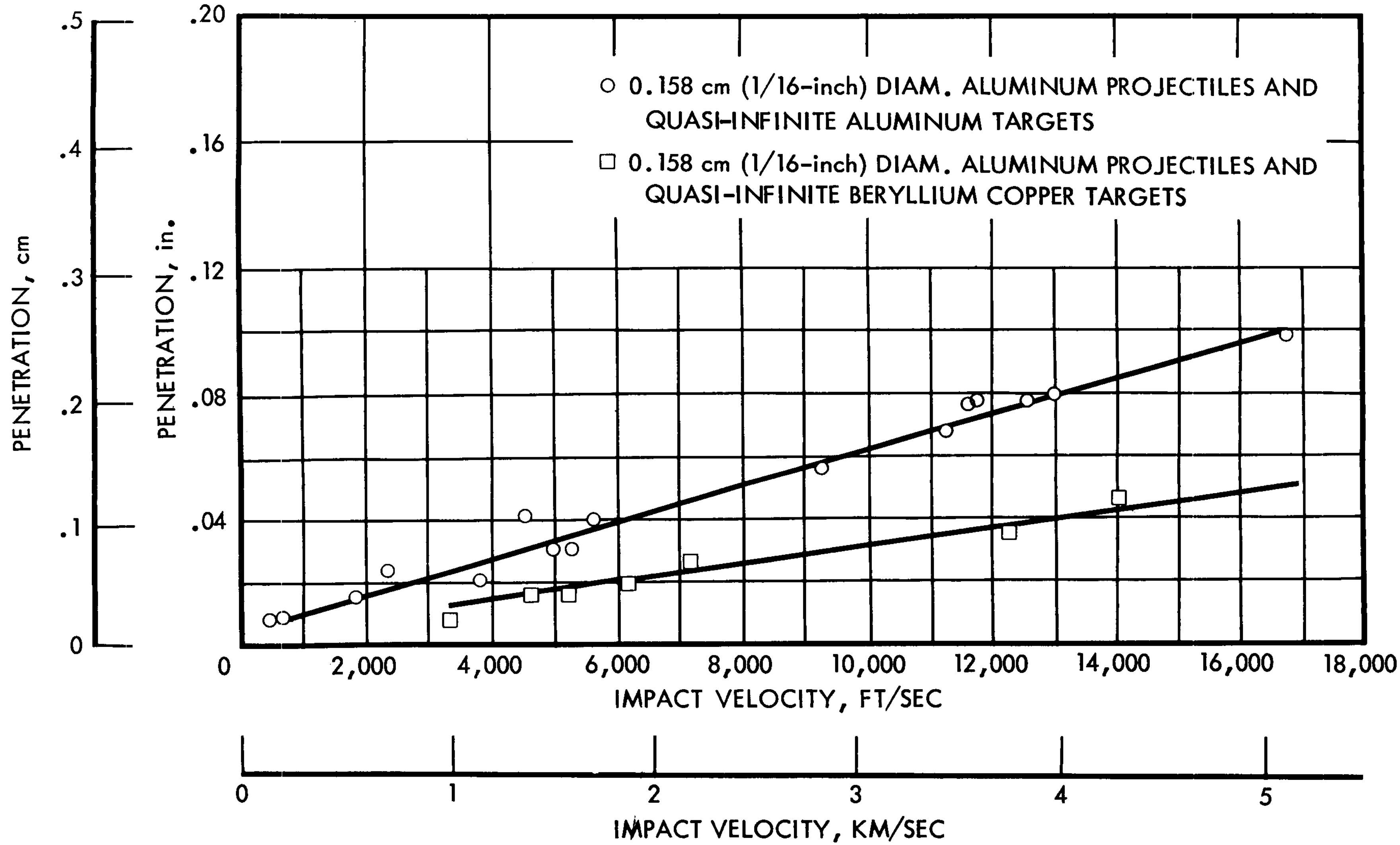



FIGURE 10 - PENETRATION DEPTH CORRELATION

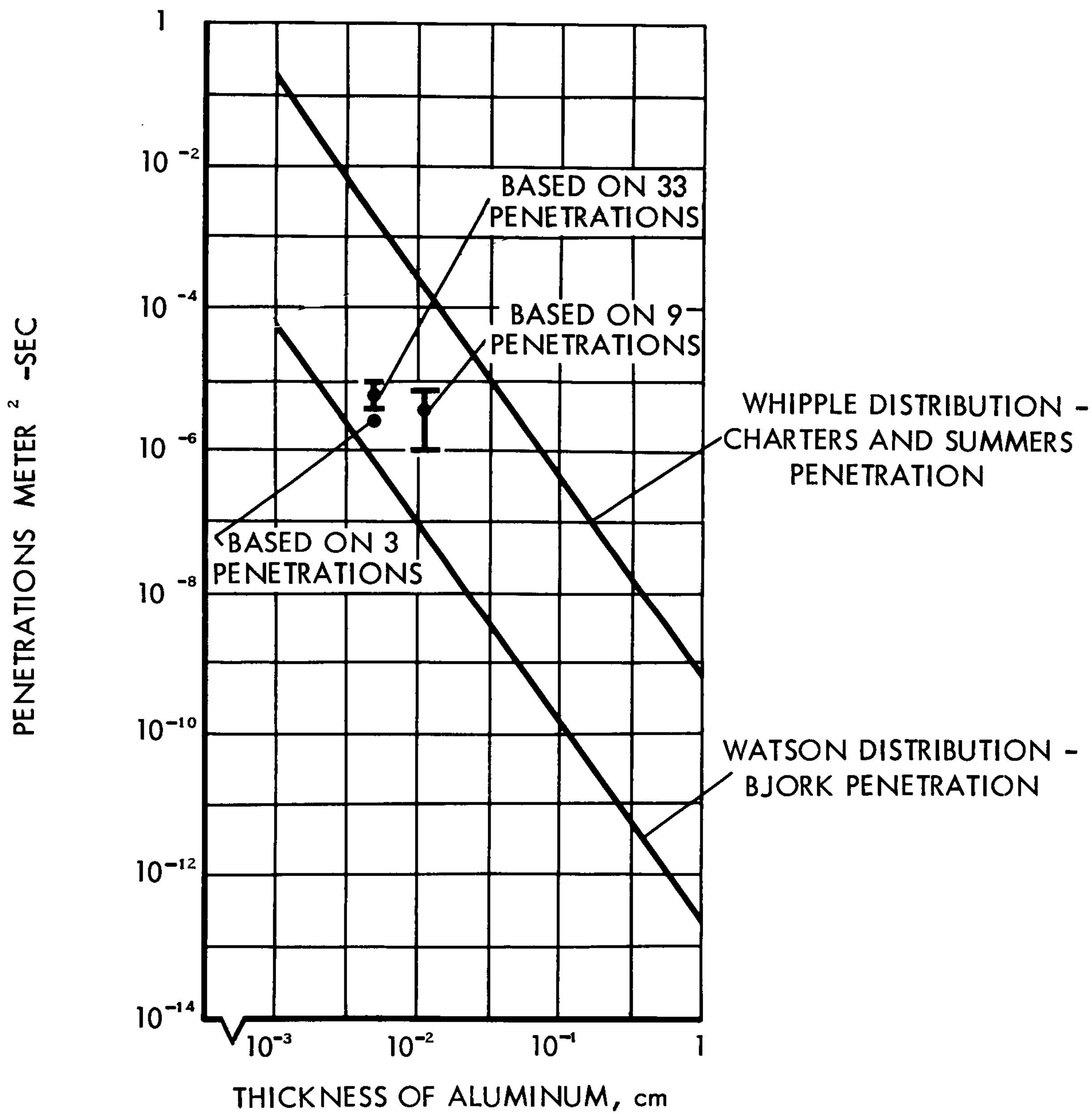



FIGURE 11 - EXPLORER XVI PENETRATION RATES AND COMPARISON WITH TWO ESTIMATES

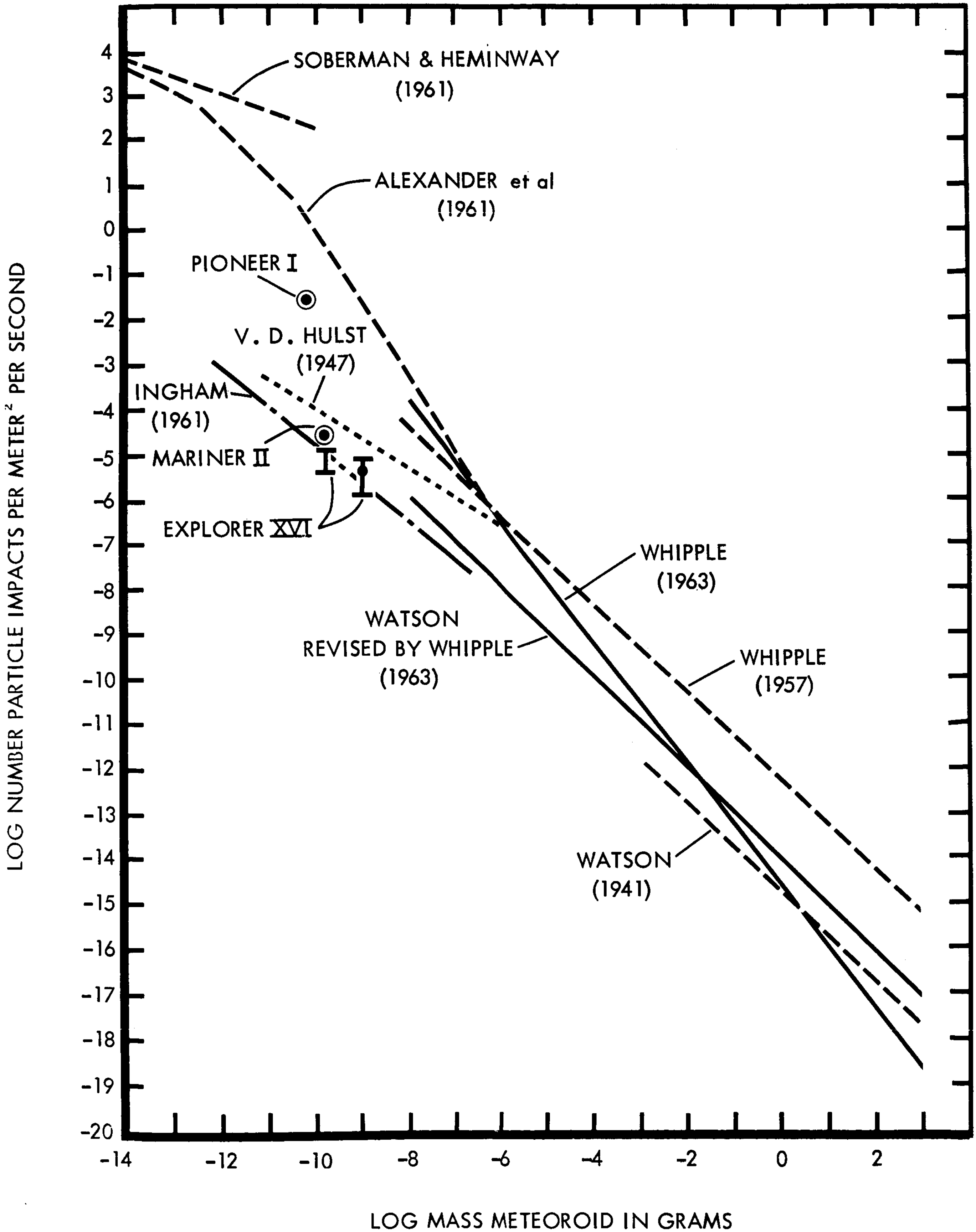



FIGURE 12 - CUMULATIVE METEOROID IMPACT RATES

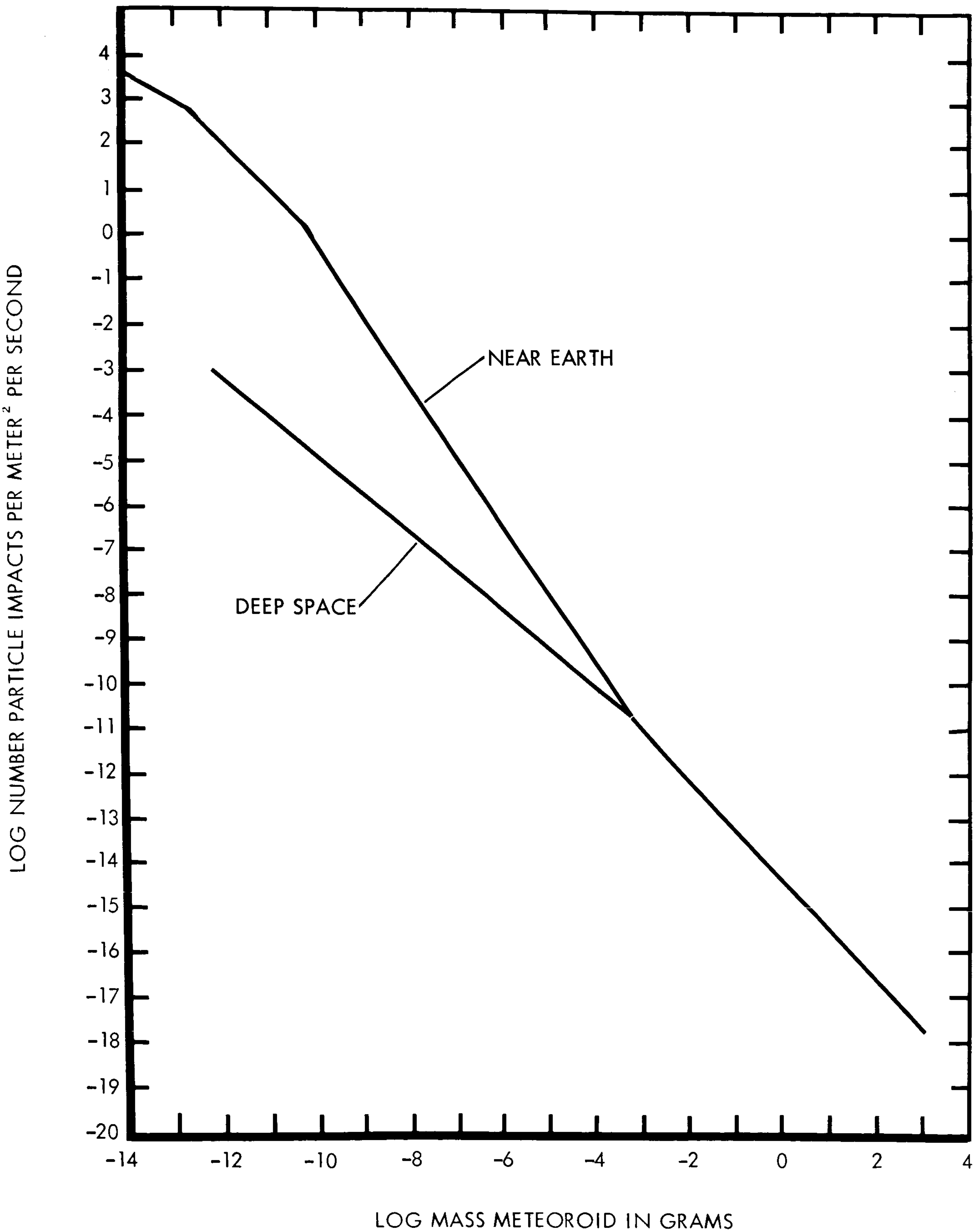



FIGURE 13 – AVERAGE CUMULATIVE METEOROID IMPACT RATES